Modeling the Transient Effects during the Hot-Compression of Wood-Based Composites

by

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(Abstract)

A numerical model based on fundamental engineering principles was developed and validated to establish a relationship between process parameters and the final properties of wood-based composite boards. The model simulates the mat formation, then compresses the reconstituted mat to its final thickness in a virtual press. The number of interacting variables during the hot-compression process is prohibitively large to assess a wide variety of data by experimental means. Therefore, the main advantage of the model based approach that the effect of the hot-compression parameters on the final properties of wood-based composite boards can be monitored without extensive experimentation.

The mat formation part of the model is based on the Monte Carlo simulation technique to reproduce the spatial structure of the mat. The dimensions and the density of each flake are considered as random variables in the model, which follow certain probability density distributions. The parameters of these distributions are derived from data collected on industrial flakes by using an image analysis technique. The model can simulate the structure of a three-layer oriented strandboard (OSB) mat as well as the structure of random fiber networks. A grid is superimposed on the simulated mat and the number of flakes, the thickness, and the density of the mat at each grid point are computed. Additionally, the model predicts the change in several void volume fractions within the mat and the contact area between the flakes during consolidation. The void volume fractions are directly related to the physical properties of the mat, such as thermal conductivity, diffusivity, and permeability, and the contact area is an indicator of the effectively bonded area within the mat.

The heat and mass transfer part of the model predicts the change of air content, moisture content, and temperature at designated mesh points in the cross section of the mat during the hot-compression. The water content is subdivided into vapor and bound water components. The free water component is not considered in the model due to the low (typically 6-7 %) initial moisture content of the flakes. The gas phase (air and vapor) moves by bulk flow and diffusion, while the bound water only moves by diffusion across the mat. The heat flow occurs by conduction and convection. The spatial derivatives of the resulting coupled partial differential equations are discretized by finite differences. The resulting ordinary differential equation in time is solved by a differential-algebraic system solver (DDASSL). The internal environment within the mat can be predicted among different initial and boundary conditions by this part of the hot-compression model.

In the next phase of the research, the viscoelastic (time, temperature, and moisture dependent) response of the flakes was modeled using the time-temperature-moisture superposition principle of polymers. A master curve was created from data available in the literature, which describes the changing relaxation modulus of the flakes as a function of moisture and temperature at different locations in the mat. Then the flake mat was compressed in a virtual press. The stress-strain response is highly nonlinear due to the cellular structure of the mat. Hooke's Law was modified with a nonlinear strain function to account for the behavior of the flake mat in transverse compression. This part of the model gives insight into the vertical density profile formation through the thickness of the mat.

Laboratory boards were produced to validate the model. A split-plot experimental design, with three different initial mat moisture contents (5, 8.5, 12 %), three final densities (609, 641, 673 kg/m^3 or 38, 40, 42 lb/ft^3), two press platen temperatures (150, 200 °C), and three different press closing times (40, 60, 80 s) was applied to investigate the effect of production parameters on the internal mat conditions and the formation of the vertical density profile. The temperature and gas pressure at six locations in the mat, and the resultant density profiles of the laboratory boards, were measured. Adequate agreement was found between the model predicted and the experimentally measured temperature, pressure, and vertical density profiles.

The complete model uses pressing parameters (press platen temperature, press schedule) and mat properties (flake dimensions and orientation, density distribution, initial moisture content and temperature) to predict the resulting internal conditions and vertical density profile formation within the compressed board. The density profile is related to all the relevant mechanical properties (bending strength, modulus of elasticity, internal bond strength) of the final board. The model can assist in the optimization of the parameters for hot-pressing wood-based composites and improve the performance of the final panel.

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List of Symbols

Constants

R = universal gas constant 8.31696 (J / mol / K)
M_a = molar weight of air 0.028968 (kg / mol)
M_v = molar weight of vapor 0.018016 (kg / mol)
ρ_{cw} = density of the cell wall 1500 (kg / m^3)

Symbols

A = reaction constant
C = specific heat of wet wood (J / m^3 / K)
C_p = heat capacity (J / kg / K)
D_{AB} = binary gas diffusivity for air – vapor mixture (m^2 / s)
D_{eff} = effective gas diffusivity (m^2 / s)
D_m = mat gas diffusivity (kg / m / s)
D_b = bound water diffusivity (kg s / m^3)
$D(t)$ = Creep Compliance (1 / Pa)
$E(t)$ = Relaxation Modulus (Pa)
E = Young's Modulus (Pa)
E_{cw} = Young's Modulus of the cell wall (Pa)
E_{i} = modulus of the spring (Pa)
E = activation energy (J / mol)
F = extent of reaction (cure index)
G = heat generation (J / m^3)
K_g = specific gas permeability of dry wood (m^3 / m)
K_m = mat superficial gas permeability (s)
L = board dimension (m)
L_{i} = dimension of column (m)
M = moisture (%)
M_{p} = molar weight (kg / mol)
P = total pressure (Pa)
R = universal gas constant (J / mol / K)
S = entropy (J / mol / K)
T = temperature (K)
T_{g} = glass transition temperature (°C)

a (T, M) = temperature and moisture shift factor
c_p = heat convection flux ($J/m^2/s$)
h_p = enthalpy (J/kg)
k = thermal conductivity
n_p = mass flux ($kg/m^2/s$)
n = order of reaction
p = partial pressure (Pa)
q = heat conduction flux ($J/m^2/s$)
t' = reduced time (s)
t = time (s)

α = attenuation factor for vapor diffusivity in the flakes
ϵ = strain
ϵ_y = yield strain of the cell wall (0.015 for wood)
Θ = rotation angle (deg)
ϕ_1, ϕ_2 = degree of alignment (deg)
η = viscosity ($kg/m/s$)
η_i = viscosity of the dashpot ($kg/m/s$)
λ = heat of vaporization (J/kg)
μ = expansion ratio
μ_p = chemical potential (J/kg)
ρ_a = density of air (kg/m^3)
ρ_b = density of bound water (kg/m^3)
ρ_d = density of dry wood (kg/m^3)
ρ_r = relative density
$\rho_r(\epsilon)$ = relative density function
ρ_v = density of vapor (kg/m^3)
σ = stress (Pa)
τ = retardation or relaxation time (s)
$\psi(\epsilon)$ = nonlinear strain function
ζ_{lf} = lumen fraction in the flakes
ζ_{sm} = space fraction in the mat
ζ_{vm} = void (space + lumen) fraction in the mat
ζ_{lm} = lumen fraction in the mat

$\mathcal{H}^j$ = external heat transfer coefficient ($J/m^2/s/K$)
$\mathcal{K}^j$ = external bulk flow coefficient (m)
$\mathcal{D}^j$ = external diffusion coefficient (m/s)

Superscripts

B = boundary point
b = bottom boundary
edge = left and right boundary
face = top and bottom boundary
j = represents boundaries (top, bottom, left, right)
l = left boundary
r = right boundary
t = top boundary
∞ = environment
y = horizontal coordinate in the width of the board
z = vertical coordinate in the thickness of the board

Subscripts

E = east from the actual point
L = longitudinal anatomical direction in solid wood
N = north form the actual point
P = actual point
S = south from the actual point
T = transverse (radial and tangential) anatomical direction in solid wood
W = west from the actual point

a = air
b = bound water
cw = cell wall
d = dry wood
dp = dew point
e = east interface
f = flake
fsp = fiber saturation point
g = gas phase (air + vapor)
i = x direction
j = y direction
k = z direction
l = lumen (hole in the flake)
m = mat
n = north interface

p = phase (air, vapor, bound water)
s = space (hole in the mat)
s = south interface
sat = saturation
v = vapor
v = void (space + lumen)
w = water
w = west interface